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13. ABSTRACT (Maximum 200 words)

The performance of the best velocity estimators was determined using a new technique that does not require in situ measurements to estimate the statistical performance of velocity estimates. A new theoretical prediction of the effects of the pulse averaging of the wind field on estimates of the spatial structure function and the variance of the velocity field has excellent agreement with simulations and the measurements from data. The conditions under which corrections for the effects of pulse averaging can be performed were determined. This permits accurate estimates of the velocity variance, the velocity structure function, and the energy dissipation rate when Kolmogorov scaling is valid or when a valid model exists for the spatial statistics. The performance of coherent Doppler lidar in the weak signal regime was determined by computer simulations and from data. Profiles of atmospheric statistics (mean velocity, velocity variance and energy dissipation rate for various lidar beam angles) were produced with corrections for the spatial averaging by the lidar pulse. Estimation algorithms for Doppler lidar data from cloudy regions were developed to handle high velocity shear and large gradients in backscatter. High resolution in situ measurements of atmospheric turbulence using an instrumented kite platform were produced.

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## FINAL PROGRESS REPORT FOR U.S. ARMY RESEARCH OFFICE

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3. TITLE OF PROPOSAL: Analysis of Coherent Lidar Data
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## STATEMENT OF THE PROBLEM STUDIED

High spatial and temporal resolution measurements of wind fields are essential for understanding and predicting atmospheric processes. Recent advances in solid-state lasers have produced coherent Doppler lidar with improved performance. The performance is defined by the accuracy and bias of the wind measurements and by the ability to extract useful information from the data. The statistical behavior of the velocity estimates is completely described by the probability density function (PDF). The parameters of the PDF can be extracted from data and compared with the predictions of ideal computer simulations and the predictions of theoretical performance for a wide variety of conditions and for various velocity estimation algorithms.

## SUMMARY OF RESULTS

The performance of the best velocity estimators was determined using a new technique that does not require in situ measurements to estimate the statistical performance of velocity estimates. This includes the fraction of outliers in the low signal to noise regime and the estimation error of the good velocity estimates. The velocity accuracy with sufficient to perform the first Doppler lidar estimates of the spatial structure function of the radial velocity in both the horizontal and vertical direction. The Kolmogorov scaling was observed as well as the effects of the pulse averaging of the wind field by the sensing volume of the pulse over the measurement range gate.

For typical boundary layer experiments, a spatial array of in situ wind sensors would be required to produce a statistically reliable comparison of coherent Doppler lidar wind measurements. A new theoretical prediction of the effects of the pulse averaging of the wind field on estimates of the spatial structure function and the variance of the velocity field has excellent agreement with simulations and the measurements from CTI's data. The conditions under which corrections for the effects of pulse averaging can be performed were determined. This permits accurate estimates of the velocity variance, the velocity structure function, and the energy dissipation rate when Kolmogorov scaling is valid or when a valid model exists for the spatial statistics.

The performance of coherent Doppler lidar in the weak signal regime was determined by computer simulations using the best velocity estimators. Threshold signal levels were defined for useful and good data based on the fraction of the estimates that were random outliers due to the fading in the return signal. The dependence on threshold signal level $S$ with the number of lidar pulses $N$ used for each estimate produced simple empirical curves of the form $S = KN^{-a}$ were $a \approx 0.75$ for small $N$ and $a \approx 0.5$ for large $N$. The statistical accuracy of the good velocity estimates at the threshold signal level was approximately constant as a function of $N$. This simplifies system design analysis. One of the numerically efficient estimators had good performance with large $N$, which was a surprise since it does not perform well for single pulse data.

Improved algorithms for extracting the performance of velocity estimators with wind turbulence included were also produced. These algorithms permit robust parameter estimation for a wide variety of conditions. A theoretical correction for the effect of spatial filtering by the lidar pulse was shown to be in good agreement with the results from computer simulations. The theoretical corrections are numerically efficient and permits fast evaluation of many realistic conditions. Both correction algorithms were applied to Doppler lidar data collected in the convective boundary layer. With the pulse-

correction, the spatial structure function of the Doppler lidar radial velocity agrees with the Kolmogorov scaling and therefore produces an estimate of the energy dissipation rate which is unbiased, i.e., an estimate that should agree with in situ measurements. This agreement was also found for a lidar beam transmitted at 30 and 45 degrees from zenith and inside regions of high shear, provided that the fluctuations around the mean velocity were used for estimating the statistics. Profiles of atmospheric statistics (mean velocity, velocity variance and energy dissipation rate for various lidar beam angles) were produced with corrections for the spatial averaging by the lidar pulse. All the wind statistics produced were true spatial statistics and did not require Taylor's frozen hypothesis to convert a temporal statistic to a spatial statistic using the mean velocity. Many important spatial wind statistics can now be investigated with coherent Doppler lidar.

Estimation algorithms for Doppler lidar data from cloudy regions were developed to handle high velocity shear and large gradients in backscatter. The new algorithms will be applied to Doppler lidar data for a vertically pointing beam under a cloud deck and later for fair-weather cumulus clouds. Preliminary analysis shows pulse penetration of 1 km into a cloud deck with sufficient signal level to extract useful velocity and backscatter estimates. Doppler lidar estimators were also evaluated and compared with traditional Doppler radar estimators.

High resolution in situ measurements of atmospheric turbulence using an instrumented kite platform were produced. The spatial spectrum of temperature fluctuations was in excellent agreement with Kolmogorov scaling. The intermittency of the turbulence was studied using 4 second estimates of the turbulence structure constant. These are very promising results which can be extended to produce high spatial and temporal resolution local profiles of turbulent quantities using multiple sensors suspended from a kite platform.

## LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS FUNDING PERIOD

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"Maximum likelihood estimators for Doppler radar and lidar," R. G. Frehlich, submitted to IEEE Trans. Geosci. Remote Sensing

"Evaluation of coherent Doppler lidar velocity estimators for clouds," B. T. Lottman and R. G. Frehlich, submitted to Appl. Opt.

"The use of state-of-the-art kites for profiling the lower atmosphere," B.B. Balsley, M. L. Jensen, and R. G. Frehlich, Boundary-Layer Meteorology, in press.

"Coherent Doppler lidar measurements of wind field statistics," Rod Frehlich, Stephen M. Hannon, and Sammy W. Henderson, Boundary-Layer Meteorology, in press.

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